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Hypothetical Explanations of the Negative Apparent Effects of Cloud Seeding in the Whitetop Experiment

(rainfall/randomization/stratification)

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ABSTRACT **In order to explain the apparent losses of rain ascribable to seeding at the Whitetop trial, particularly large and highly significant in the stratum E (but not in the opposite stratum W) of experimental days, it has been hypothesized that seeding causes widespread cloudiness and subsequent lowering of ground temperatures. This hypothesis is flatly contradicted by the observations: the seeded E-days (but not W-days) were uniformly less cloudy and hotter than those without seeding. Curiously, these differences prevailed not only from the scheduled time of seeding but also for several hours beforehand. The average rainfall for the 10 hr that preceded the time of seeding was investigated in eight "cells", defined by the day's wind direction to be downwind, upwind, and to the sides and "far" and "near" the center of seeding. Highly significant decreases were found in the far-upwind and far-left cells, indicating an early-morning disparity between those E-days that later were declared as experimental to be seeded and those E-days that were declared as experimental not to be seeded. This disparity, difficult to explain by chance variation, suggests that particular caution be used in treating differences in the rainfall between seeded and not-seeded days in the Whitetop trial as having been caused by seeding.**

In the Whitetop randomized cloud-seeding experiment performed by Braham (1) there was a deficiency of rainfall on the 102 days with seeding as compared to the 96 experimental days without seeding. Three interpretations have been suggested for the large difference in rainfall, which extended over an area of at least 100,000 square miles. According to Battan (2), because no mechanism is known whereby seeding could produce effects in the upwind areas, the noted apparent losses of rain in the Whitetop experiment could not have been caused by seeding. Contrary to this, Tribus (3) hypothesized that the deficiencies of rain on seeded days were due to overseeding. The same hypothesis of overseeding, at least for the central 10,000 square miles, was adopted by Braham and Flueck (4). A third hypothesis, which we shall call the cloudiness–temperature (or C–T) hypothesis, was formulated by J. Hughes* (personal communication). Hughes' hypothesis is specific and offers the possibility of verification.

The purpose of this paper is to report on our efforts to verify the C–T hypothesis. The results are in the negative: the cloudiness–temperature hypothesis is flatly contradicted by the data. However, the same data suggest the possibility that the noted deficiencies of rain on seeded days are due to some problems of effective randomization. This possibility is confirmed by additional analysis of rainfall data.

THE CLOUDINESS–TEMPERATURE HYPOTHESIS

The explanatory hypothesis proposed by Hughes is based on the diurnal variation in the hourly precipitation amounts (5) on seeded and on not-seeded experimental days. On days without seeding, the average hourly precipitation shows a very marked maximum in the afternoon hours. On days with seeding, this maximum is practically absent. Because of Braham's intention (1) to seed primarily the air mass convective clouds, frequently connected with afternoon thunderstorms, Hughes hypothesized that the mechanism of the observed apparent effects of seeding involves a decrease in the afternoon thunderstorm activity. One possibility is that the immediate result of seeding, which began at 10 or 11 a.m., was the development of widespread cloudiness. If so, then afternoon ground temperatures would have been somewhat cooler than otherwise, and there would have been fewer thunderstorms.

Thus, in order to verify the C–T hypothesis, it is sufficient to establish whether or not the beginning of seeding at the Whitetop trial was generally followed by increased cloudiness and somewhat cooler ground temperatures in the afternoon.

DEFINITION OF E- AND W-DAYS

In two earlier studies (6, 7), an effort was made to classify all of the 198 experimental days of the Whitetop trial into two approximately equal strata, hopefully with different patterns of apparent effects of seeding. Three of these stratifications (6) are based on differently defined degrees of conformity of winds aloft with the objective rule used by Braham to select days for the experiment. This rule required that the 8 a.m. wind 4000 ft (1.219 km) above West Plains, Missouri be between 170° and 340°, inclusive. The fourth classification used, with strata of air-mass and of frontal days, was determined for us by Chin and Neiburger, to whom we are indebted. All four classifications proved very effective. The stratum of days "not conforming" with Braham's rule, and also the stratum of air-mass days, showed significant and highly-significant apparent losses of rain ascribable to seeding, but the opposite stratum of each classification did not.

Obviously, if the C–T hypothesis has any validity, the hypothesized effects must be most pronounced in the strata of days with the sharpest apparent losses of rainfall. The stratum that exceeds all others in this particular respect is that labeled E-days. Thus, for brevity, the attempted veri-

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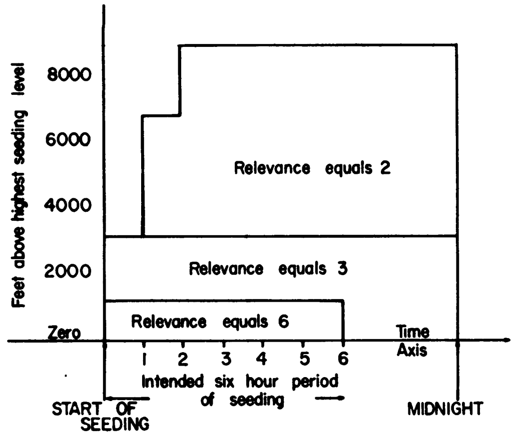

FIG. 1. Definition of E- and W-days with the use of West Plains pibal soundings from 10 a.m. to midnight of experimental days.

fication of the C–T hypothesis reported below is limited to the stratum of E-days, and to the opposite stratum of W-days.

The published definition of E- and W-days (6) is in somewhat general terms. The precise definition follows. It is based on wind directions over West Plains provided by pibal soundings from 10 a.m. to midnight of each experimental day.

The term E-wind is used to describe the wind with direction between 0° and 180°, inclusive. Dependent upon the time when an E-wind is observed and dependent upon the level at which it is observed, it is assigned a degree of "relevance", 2, 3, or 6. An experimental day is labeled an E-day if the total degrees of relevance of winds observed on that day is 6 or more. All other days are labeled W-days.

(*a*) An E-wind *at the level of seeding* observed at any time during the 6 hr that follow the scheduled start of seeding (either 10 or 11 a.m.) is assigned 6 units of relevance. If observed later, this E-wind is assigned 3 units of relevance.

(*b*) An E-wind *at 2000 ft* (*.6095 km*) *above the level of seeding* observed at any time up to midnight is assigned 3 units of relevance.

(*c*) 2 units of relevance are assigned to E-winds *4000 ft or 6000 ft* (*1.828 km*) *above seeding level* if they were observed later than 1 hr after the intended start of seeding; the same assignment of relevance is given to E-winds *8000 ft* (*2.437 km*) *above seeding*, provided they are observed at least 2 hr after the start of seeding. A diagrammatic presentation of the above definition is given in Fig. 1.

This definition of E-days was arrived at on intuitive grounds, with an effort to have the two strata E and W about equal in size. No significant apparent effects of seeding were found for W-days. For E-days, the apparent effect of seeding on rain in the whole area studied, up to 180 miles from target center, was a 46% apparent loss of rain, significant at $P = 0.005$. Also, the subsequent study (7) showed significant apparent losses of rain of up to 75% in areas not only downwind, but also upwind and to the sides.

CLOUDINESS AND TEMPERATURE ON E- AND W-DAYS AT 8 UNITED STATES WEATHER BUREAU STATIONS

If the C–T hypothesis corresponds to reality, then from the early afternoon on, the cloudiness on seeded E-days must be higher than on those without seeding. Also, the afternoon temperatures on seeded E-days must be cooler than on not-seeded E-days. The results of the test of the C–T hypothesis, separately for E- and for W-days, are exhibited in Fig. 2, which refers specifically to cloudiness. Each of the eight rows refers to a station in the area for which the relevant observations are published. These stations are spread, with an approximate uniformity, over the whole area studied, up to 180 miles from the target center. The continuous curves exhibit the diurnal variation of the per cent of sky cover on days with seeding. The dashed curves refer to days without seeding.

The cloudiness observations on E-days flatly contradict the C–T hypothesis. At all of the eight stations, the afternoons of seeded E-days had less cloudiness than those of days without seeding.

The panels in the right column in Fig. 2 correspond to W-days. They are much less regular than those for E-days and, in some cases, suggest an opposite pattern.

Graphs have been constructed similar to those in Fig. 2, but which represent the diurnal variation in the ground-level temperature. They are in perfect harmony with those in Fig. 2 and contradict the C–T hypothesis; the afternoons of seeded E-days were invariably hotter than those on days without seeding. Briefly, the actual average weather conditions on E-days were contrary to those visualized by the C–T hypothesis. The mechanism of the disappearance on seeded E-days of the natural afternoon maximum of hourly rainfall must be different than the explanation of the C–T hypothesis.

AN EMBARRASSING DETAIL

The purpose of our constructing the graphs in Fig. 2 relating to cloudiness, and of similar graphs relating to ground temperature, was to see whether the afternoons of seeded E-days were cloudier and cooler than those of days without seeding. However, the range of the curves is not limited to afternoon and evening hours, but begins at midnight preceding the experimental day; the curves reveal what appears to be an embarrassing detail. As shown in the left column of Fig. 2, with a single exception for Fort Smith some 180 miles from the center of the target and west of the Ozark Plateau, the cloudiness on seeded E-days was less than that on not-seeded E-days, not just after the beginning of seeding but over a period of 10–11 hr before the beginning of seeding, from as early as the preceding midnight. This difference could not be due to seeding. The curves representing diurnal variation in average temperature at eight stations showed similar details; the seeded E-days were hotter than those not-seeded, not only in the afternoon but also at all times from the preceding midnight.

The above results, referring both to cloudiness and temperature, were communicated to Prof. Braham. The joint paper (4) contains comments of the two authors on the findings just reported.

DIURNAL VARIATION IN AVERAGE PRECIPITATION AMOUNTS IN AREAS DOWNWIND, UPWIND, AND TO THE SIDES OF THE SOURCE OF SEEDING MATERIAL

The results described above refer to E- and W-days, and to cloudiness and temperature, in eight different localities, irrespective of whether on some days these localities were downwind, upwind, or to the side. Because of our results (7) that indicated apparent decreases due to seeding in areas downwind and upwind, it appeared interesting to examine the diurnal change in hourly amounts of precipitation that fell both downwind and upwind, at various distances from the center of seeding. Hence, the hourly precipitation was used to perform an "upwind–downwind" study as in (7). Any such study must be based on hourly precipitation amounts registered by recording gages. There were found only 104 such gages in the area that had either continuous records or with such gaps as could be convincingly filled by interpolations. When these were plotted on a map and an attempt was made to conduct the upwind–downwind study with the same grid of cells as used earlier (7), it appeared that on a number of experimental days there were cells that included not a single gage. In order to remedy the situation, we decided to broaden the areas of the cells, thereby decreasing their number. The following study is based on the moving grid of eight cells only. Two cells from $-45°$ to $+45°$ from the day's wind direction, one cell up to 90 miles from the seeding line, and the other from 90 to 180 miles were labeled the downwind cells. In the opposite direction, two upwind cells, "near" and "far", were formed. A similar arrangement was made with two cells on the left and two cells on the right.

For each cell, curves characterizing the diurnal variation of average hourly precipitation were constructed both for E- and for W-days; in all, 16 graphs with two curves each, were drawn. While the comparisons between these two graphs is interesting for all of the cells, Fig. 3 produces the graphs for only four "far" cells–downwind, upwind, left, and right.

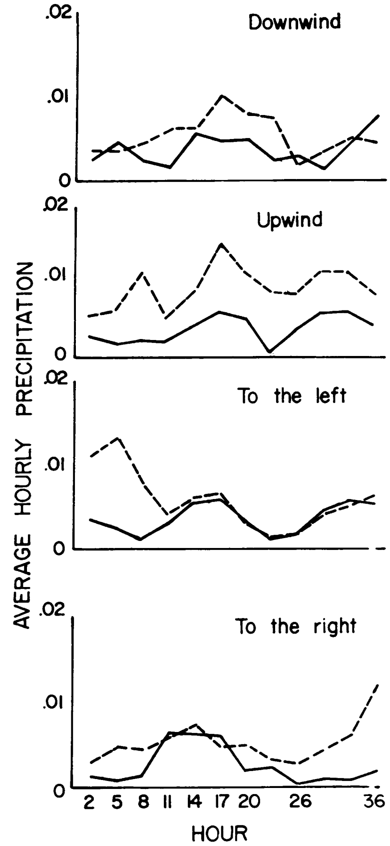

FIG. 3. Hourly precipitation in "far" cells, from midnight preceding the experimental day to noon of the next day (36 hr).

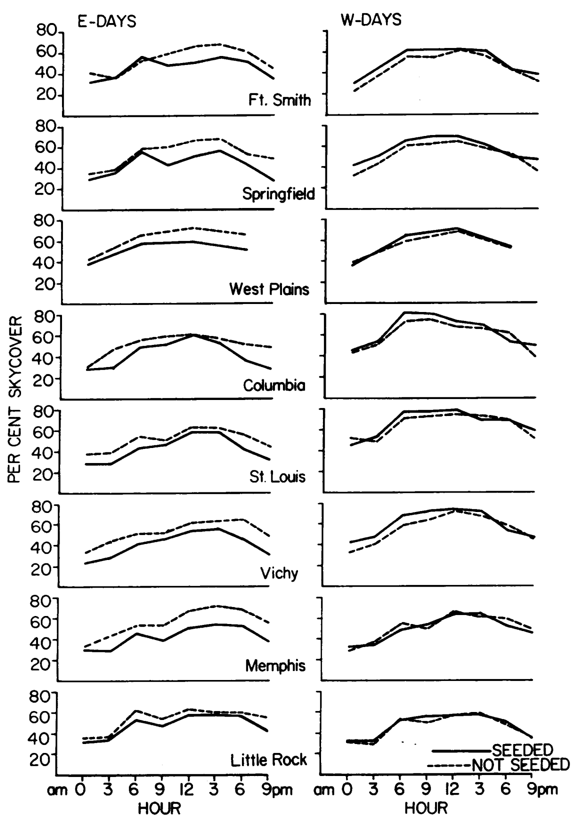

FIG. 2. Test of the C–T hypothesis. Cloudiness on E- and W-days at eight stations averaged over experimental days.

For W-days, the graphs do not exhibit an intelligible pattern, and generally confirm the earlier conclusions that the seeding had no pronounced effect. Contrary to this, on E-days, the apparent effect of seeding is striking, particularly in the far-upwind cell that was 90–180 miles away from seeding. The nonseeded curve is roughly parallel to the seeded curve, with average not-seeded-day precipitation being more than twice that on days-with-seeding, over the whole period from the midnight preceding the experimental day to noon of the next day. In the far-downwind cell, the relationship is much less regular and less pronounced. In other cells, for which the diurnal variations are not exhibited, the curves are substantially less regular.

The curious thing about the far-upwind cell is that the ratio of better than 2 to 1 in the hourly precipitation in favor of not-seeded E-days is maintained not only during the hours of seeding and later, but throughout, from the preceding midnight on. Could this be due to chance? Table 1 shows the cell-by-cell evaluation of the difference in average precipitation amounts for seeded and not-seeded E-days in the 10-hr period preceding the start of seeding. Seeding commenced at 11 a.m. during 2 years and at 10 a.m. during the other 3 years of the experiment. The arrangement of the table is similar to that in earlier publications (6, 7). The three groups of columns are intended to answer the following questions about the rain observed in the 10-hr period before the scheduled start of seeding:

TABLE 1. *Evaluation of differences in average precipitation amounts in the 10-hr period before the scheduled start of seeding for seeded and not-seeded E-days*

Cell	% Periods with rain				Inches of rain per wet period				Inches of rain per period (wet or dry)			
	S	NS	% change	*P*	S	NS	% change	*P*	S	NS	% change	*P*
Near-downwind	29	32	−10	0.88	0.136	0.120	+13	0.81	0.039	0.038	+1	0.98
Far-downwind	39	47	−16	0.57	0.074	0.091	−18	0.60	0.029	0.043	+32	0.40
Near-upwind	21	32	−33	0.33	0.251	0.178	+41	0.48	0.054	0.057	−5	0.93
Far-upwind	27	49	−45	0.04	0.079	0.130	−39	0.27	0.021	0.063	−67	0.03
Near-left	29	38	−25	0.40	0.101	0.145	−30	0.39	0.029	0.055	−48	0.20
Far-left	52	45	+16	0.60	0.041	0.221	−82	0.00	0.021	0.099	−79	0.00
Near-right	20	34	−42	0.15	0.199	0.075	+166	0.06	0.039	0.025	+54	0.50
Far-right	25	43	−41	0.10	0.068	0.103	−34	0.40	0.017	0.044	−61	0.09

(*a*) Was the frequency of days with rain in the 10-hr period significantly different for days with seeding from that for days without seeding?

(*b*) Did the average amount of rain per wet 10-hr period differ significantly from seeded to not-seeded days?

(*c*) Was the total apparent effect of seeding, combining the frequency of wet 10-hr periods and average rain per wet period, significant?

Of the eight cells, one shows a significant, and the other two a highly significant, difference between days with and without seeding. Both of the highly significant differences are in "far" cells, one upwind and one on the left. In these cells, the early-morning precipitation on seeded days amounted to one-third and one-fifth that in the corresponding period on not-seeded days. (It may be noted that because of the prevalence of southwesterly winds on experimental days, these two cells were predominantly on the Ozark Plateau.) These differences could hardly have resulted from random selection of days for seeding.

Furthermore, these differences could not have been the effect of seeding. It is appropriate to adopt the assumption that some other cause must have been operating, some problem with effective randomization.

CONCLUDING REMARK

The explanation for the decrease in precipitation during seeding examined in this paper is the possible effect of increased cloudiness and decreased temperature from seeding (the C–T hypothesis). This hypothesis is not verified by the observational data. In fact, the observations tended to the contrary. However, this contrary outcome occurred also before seeding even started; our plots started at midnight, 10 hr before any seeding began. This led to an investigation of precipitation differences during the 10-hr period that preceded seeding. Strong differences were found between the amounts of 10-hr precipitation before the scheduled start of seeding. This occurred in the "far" cells, upwind and to the left. These differences, and their significance probabilities, suggest some problems with randomization.

Whatever the reason, there is little doubt that seeded E-days had less than their fair share of days with bad weather (cloudiness and rainfall), from the early-morning hours through a 10-hr period before the scheduled start of seeding. This, rather than seeding itself, could have been the cause of the outstandingly large, negative, apparent effects of seeding—a conclusion somewhat similar to that suggested by Battan. In consequence, any conclusions about the effectiveness of seeding, one way or the other, that are based on the Whitetop experiment must be made with extreme caution.

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